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# Distributed MAP in the SpinJa Model Checker

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Spin in Java (SpinJa) is an explicit state model checker for the Promela modelling language also used by the SPIN model checker. Designed to be extensible and reusable, the implementation of SpinJa follows a layered approach in which each new layer extends the functionality of the previous one. While SpinJa has preliminary support for shared-memory model checking, it did not yet support distributed-memory model checking. This tool paper presents a distributed implementation of a maximal accepting predecessors (MAP) search algorithm on top of SpinJa.

## 1 Introduction

The SPIN model checker [6] is arguably one of the most popular explicit state model checkers to date. It can verify models defined in its Promela modelling language for absence of deadlocks, assertion violations, non-progress cycles and accepting cycles. This has proved useful in many real-world applications by tracking down problems and increasing reliability through modelling.

Spin in Java (SpinJa) [7] is a model checker written using object-oriented programming techniques. Its purpose is to be easily extensible and reusable, while staying close to SPIN in terms of usability, semantics, and performance. Whereas SPIN generates a stand-alone verifier, SpinJa reuses its code through a library. Support ranges from language constructs up to verification algorithms. In addition, the library can be easily extended due to its layered structure.

A problem inherent to all model checkers, including SpinJa, is state explosion. One way to deal with larger models is to distribute verification over multiple machines in a distributed-memory cluster. The model checker DiVinE [4] for example uses asynchronous communication to achieve nearly linear speedups in verification [11]. While SpinJa has initial support for shared-memory model checking, it lacks support for distributed-memory model checking.

This tool paper investigates how to extend SpinJa with support for distributed-memory model checking. More specifically, it describes the implementation of a distributed maximal accepting predecessors (MAP) algorithm [4] in the generic layer of SpinJa. The inherent extensibility of SpinJa should make this relatively easy, but it is nevertheless interesting to see how this works out in practice. It turns out that, except for a few problems, it is indeed possible to reuse much of the SpinJa code-base in a distributed model checker.

Contributions to SpinJa cover both new features and bug fixes. New features include meta-data support for state storage and remote referencing of user-defined labels. A notable bug fix is the correct encoding and decoding of states, which is used heavily in distributed model checking. This code was not exercised thoroughly enough by SpinJa's depth-first search. In addition to the SpinJa library, the implementation contains communication facilities and termination detection.

The remainder of this paper is structured as follows. Section 2 gives an overview of SpinJa, while section 3 gives an outline of the MAP algorithm. The actual implementation of the algorithm in SpinJa is discussed in section 4 and results are presented in section 5. The paper is concluded in section 6.

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## 2 The SpinJa model checker

The Spin in Java (SpinJa) [7] model checker is designed to be extensible and reusable. To achieve this goal, SpinJa uses a layered design inspired by the framework of Mark Kattenbelt et al. [8]. SpinJa defines three layers: a generic, abstract and tool layer, see Figure 1. Each layer extends the functionality of the previous one. A parser is used to generate a compilable model, extending the tool layer, from a Promela specification. Only the tool layer is language specific. Algorithms, based on the generic layer, are language agnostic.

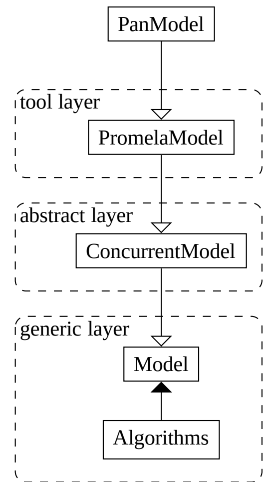



Figure 1: SpinJa layers

The generic layer models the state space of the specification using State and Transition objects. Simulation and verification algorithms manipulate the state of the Model either directly by encoding and decoding states, or indirectly by taking and undoing transitions. Since algorithms are based on generic State and Transition objects, they can easily share code, for example state hashing and storage methods.

The abstract layer introduces concurrency between Models. The ConcurrentModel defines one or more Processes which run concurrently; both ConcurrentModel and the Processes extend Model as defined by the generic layer. Partial-order reduction is implemented at this level and can limit the number of possible interleavings to improve performance.

The tool layer contains all language-specific facilities needed by the model at run-time. The PromelaModel for example implements methods to add process types and channels. A NeverClaimModel can be used to verify the absence of unwanted behavior, and a RendezvousTransition allows for rendezvous communication. This is the only language-specific layer: the generic and abstract layer can be used by any tool layer designed for a different language.

The parser uses JavaCC to translate a Promela specification to Java source-code for a compilable model. The resulting PanModel will extend the tool layer, using the run-time facilities it provides. The intermediate compilation step mirrors the architecture of SPIN and helps to improve performance by hard-coding information known at compile-time into the model.

## 3 The MAP algorithm

Accepting cycles indicate the presence of an unwanted property. The maximal accepting predecessors (MAP) algorithm [4] is based on the knowledge that states in a cycle are their own predecessor. Therefore, an accepting state is on a cycle if and only if it is its own predecessor. Detecting this condition by keeping track of every accepting predecessor for each visited state can significantly increase memory requirements. Storage for a single state can increase linearly with the number of accepting states in the model. The MAP algorithm prevents this problem by storing only one accepting predecessor for each state.

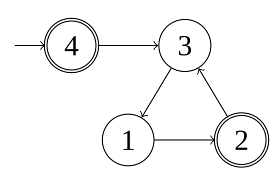



Figure 2: Accepting cycle

Storing a single accepting predecessor per state can however prevent accepting cycles from being detected. The MAP algorithm assumes a complete ordering of all accepting states in the state space and will propagate to descendants only the accepting predecessor which is maximal with respect to this ordering. However, when an accepting state on an accepting cycle is being dominated by another accepting state outside of the accepting cycle, it will not be detected as its own predecessor. See Figure 2: the accepting state 2 is dominated by the accepting state 4.

This problem is of no consequence if the dominating accepting state is itself part of an accepting cycle. The goal of the algorithm is to find only one accepting cycle, not all accepting cycles. One counter-example is enough to disprove a property. However, if the dominating accepting state is not part of an accepting cycle, then it needs to be removed as an accepting state from the state space. This will allow the MAP algorithm to run for a second iteration, without the state dominating other accepting states. By iteratively changing accepting states to non-accepting states, it becomes possible to detect any accepting cycle in the state space. This process will continue until there are no more accepting states in the state space, or until an accepting cycle has been found.

In each iteration, information on accepting states is propagated to all descendants. Nodes store information on the maximal accepting predecessor encountered by states so far. The algorithm keeps track of new accepting states it encounters, which can be removed from the next iteration if they are not part of a cycle. Accepting states which are dominated, and therefore won't be propagated, are not removed at the end of an iteration, since it is possible for them to be part of an undetected cycle.

## 4 Implementing MAP in SpinJa

In the implementation (available at [2]), communication for the MAP algorithm is handled by the Ibis Portability Layer (IPL) [3]. Ibis is a Java-based grid programming environment allowing for highly efficient communication through its IPL communication library. It also provides a convenient method for peer discovery: a registry which can be used to coordinate the pool of workers for the MAP algorithm.

The primary goal of the MAP implementation is to find cycles containing accepting states. Accepting states are typically defined by Promela never-claims, which in turn can be derived from linear-temporal-logic (LTL) properties. Many of these properties, for example those from the BEEM [10] database, reference specific labels in the verification model. SpinJa supported accept, progress and end labels in general, but only at the parser level. In particular, there was no support for user-defined labels or for differentiating between different instances of the already supported labels. (Promela defines accept, progress and end labels by prefix.) Support for labels had to be lifted to the run-time model of the verifier to allow for these remote references in LTL properties.

Distributed MAP makes heavy use of SpinJa's encode and decode functions. Each worker is in a continuous loop of decoding a state, calculating its successors and encoding these successors for shipment to other workers. While SpinJa supports both breadth-first (BFS) and depth-first (DFS) searches, mainly its DFS implementation had been thoroughly tested. Instead of encoding and decoding model states, a sequential DFS relies on the ability to take and undo specific transitions. It turned out that the encode and decode functions worked incorrectly when decoding a state sufficiently different from the current state. (New processes when created during a decode would get an incorrect process id.) A situation which does not occur in a DFS, but occurs frequently in a BFS or distributed searches.

Transitions in SpinJa can store meta-data. This is for example useful when performing a partial-order reduction to mark reduced transitions, or when interleaving a never-claim to indicate which transitions cause a context switch. States, however, do not support the storage of meta-data. The DFS algorithm in SpinJa circumvents this problem by appending meta-data to the state vector. However, this significantly increases the stored state space, since the store does not differentiate between the original state vector and the added meta-data.

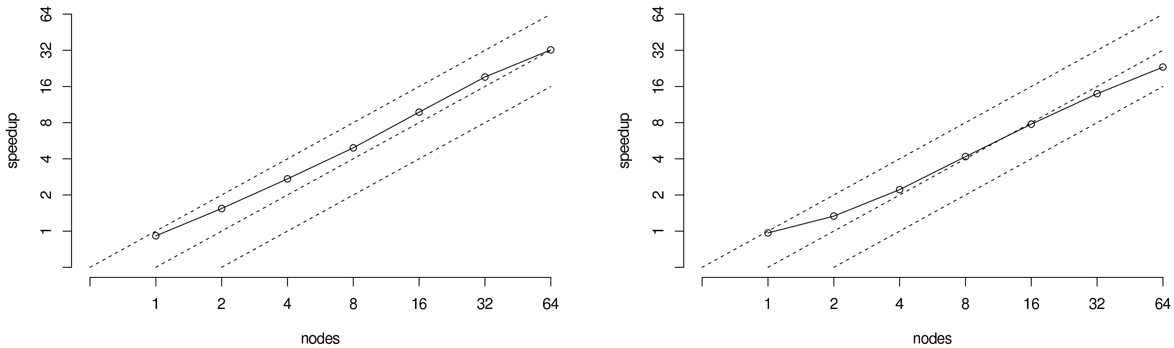
In a MAP algorithm it is necessary to store the maximal accepting predecessor propagated to states during execution: each state has an associated MAP state. To support the storage of state meta-data, SpinJa's ProbingHashTable had to be modified to allow explicit storage of meta-data for the states it contains.

Listing 1: Distributed MAP iteration

```
private boolean doIteration(byte iteration, SendPort[] senders) throws IOException {
    boolean flush = false;
    int shrink = 0;

    while (true) {
        while (!controlQueue.isEmpty()) {
            switch (processControl(controlQueue.remove(), senders, flush)) {
                case TERMINATE: return false;
                case ITERATE: return true;
                case FLUSH:
                    workStack.clear();
                    flush = true;
            }
        }

        while (!workStack.isEmpty() && controlQueue.isEmpty()) {
            shrink += processWork(workStack.pop(), iteration, senders);
            pollForMessages(flush);
        }

        while (!tokenQueue.isEmpty() && controlQueue.isEmpty() && workStack.isEmpty()) {
            processToken(tokenQueue.remove(), shrink == 0, senders);
        }

        if (controlQueue.isEmpty() && workStack.isEmpty() && tokenQueue.isEmpty()) {
            sendQueues(senders);
            blockForMessages(flush);
        } else {
            pollForMessages(flush);
        }
    }
}
```

At the heart of the distributed MAP algorithm lies the doIteration() method shown in Listing 1. It represents the main loop for each iteration of the MAP algorithm. Communication is achieved using asynchronous message passing, similar to the DiVinE [4] cluster model checker. The idea is to minimize the influence of network latency and optimize parallelism by hashing each generated state to a worker node and buffering it at the recipient.Termination is detected using a modified version of Safra's termination detection algorithm [5].

The controlQueue, stateQueue and tokenQueue store received messages until they can be processed. These queues have an inherent priority ordering: the controlQueue has the highest priority, followed by the stateQueue, while the tokenQueue has the lowest priority. The controlQueue stores messages which have an immediate influence on the control flow of the algorithm. A FLUSH control message prevents any further states from being processed, for example when a cycle has been found. The ITERATE and TERMINATE control messages are used respectively to start a new iteration or to finish the algorithm. The choice to ITERATE or TERMINATE depends on whether any accepting states were dominated in the last iteration. The stateQueue stores states which need to have their successors calculated. Successor states are hashed to find an owner node and are subsequently sent to that node. Finally the tokenQueue stores tokens used for termination detection. These should only be processed when the worker suspects the iteration to be finished: in other words when the stateQueue is empty.




(a) reader_writer (R=20, W=20, ERROR=1) (b) firewire_link (N=5, APPLICATION=0)

Figure 3: Scalability

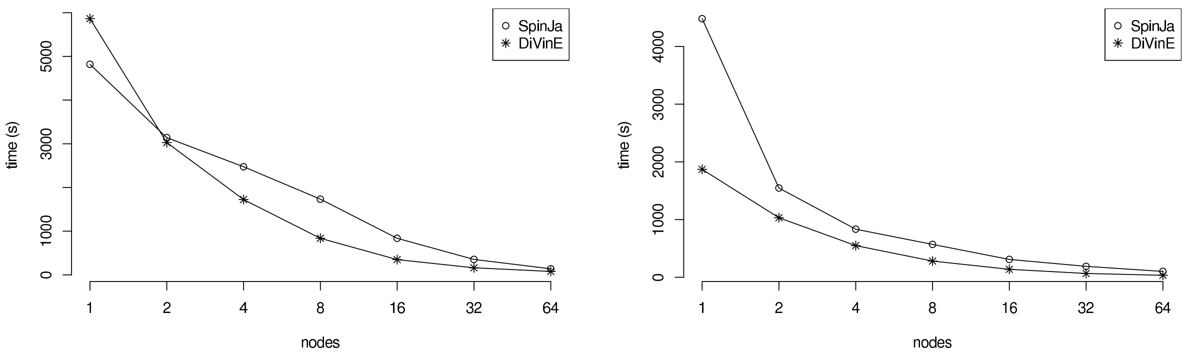
During the iterations the algorithm maintains two implicit sets: an exclude-set and a shrink-set. The exclude-set contains accepting states which should be ignored because they are not part of a cycle. This set is necessary since SpinJa contains no facilities to remove a state as accepting from the model. The shrink-set contains accepting states which are candidates for removal in the next iteration. States are both added and removed from this set during an iteration: newly encountered accepting states are added to the set, while dominated accepting states are removed. Should the iteration finish executing due to an ITERATE control message, then the shrink-set is added to the exclude-set before executing the next iteration.

# 5 Results

In lieu of more thorough performance optimizations, the implementation has been tested on the DAS-4 cluster [1] with four models from the BEEM database [10]: reader_writer, firewire_link, lamport and elevator. The sizes of these models range from approximately 600 million states (lamport), through 70 million (reader_writer) and 60 million states (firewire_link), to 10 million states (elevator). The graphs in Figure 3 show the scalability of reachability searches for two models. A comparison with the DiVinE model checker is made in Figure 4 using respectively a reachability and a cycle search of the remaining two models.

Comparing the performance of the distributed MAP algorithm with sequential DFS and BFS in SpinJa, shows the clear impact of communication overhead. For example, a single node reachability search of the BEEM bakery.5 model, without network communication, takes DFS 29.1 seconds, BFS 34.3 seconds, and MAP 39.7 seconds. In comparison, enforcing network communication (loop-back) for this single node in the MAP algorithm increases its computation time to 50.1 seconds.

The scalability graphs in Figure 3 show an average efficiency above or around 50%. The base used in these graphs is the running time of a single-node DFS. The dotted lines respectively indicate 100%, 50%, and 25% efficiency. It can be seen, when scaling up from a single node, that the algorithm looses efficiency because of an increased amount of non-local network communication. At higher node counts the initial setup of network connections becomes increasingly significant as connection setup time increases, and the total running time decreases.




(a) lamport (N=5, ERROR=1) (b) elevator (FLOORS=5, PERSONS=3)

Figure 4: Comparison

Comparing the performance of the distributed MAP algorithm with DiVinE in Figure 4 shows that the results are of a similar order. In this case the graph uses the total running time instead of scalability, since the nested DFS algorithm used for cycle searches in SpinJa is not optimal (due to the lack of generic meta-data storage). Scalability of DiVinE is more predictable than that of the presented MAP algorithm, even though results are generally close.

Clearly some performance optimizations are still required. The improvements described by Verstoep et al. [11] should prove valuable: combining messages, automatic tuning of the polling rate, prioritisation of timing critical communication and avoiding congestion while flushing message queues.

# 6 Conclusion

The goal of this paper has been to explore the flexibility of the SpinJa model checker by extending it to distributed-memory model checking. Implementing a distributed MAP algorithm in SpinJa turns out to be relatively easy: except for some missing features, most of the SpinJa library can be reused as is. The exceptions are the framework for sequential search algorithms in the generic layer, and the partial-order reduction algorithm which is not equipped to handle a distributed state space. The interface of the generic layer, based on states and transitions, proves to be a good starting point for model checkers wanting to support the Promela modelling language.

In addition to the facilities provided by the SpinJa library, a distributed algorithm also requires communication facilities to distribute states. Communication is explicitly programmed throughout the implementation presented in this paper. An interesting alternative would be to extend SpinJa's framework to abstract away from those communication primitives. Aspects like termination detection could be reused between algorithms. This avenue has been explored in parallel to the implementation presented in this paper. SpinJa has been successfully employed to generate state spaces for the distributed graph algorithm framework HipG[9].

It will be interesting to see how the SpinJa implementation compares to the more generic HipG solution, when verifying large-scale models on a large distributed-memory cluster like the DAS-4 [1]. Especially after the performance improvements described in [11] have been applied to SpinJa.

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